higher temperatures in the lower troposphere increase the atmospheric geopotential thickness and raise upper-air geopotential heights above the Arctic Ocean (Fig. 5.4b). Increased geopotential heights north of 75°N weaken the normal north–south pressure gradient driving the polar vortex that creates west–east airflow aloft. In this sense, the effect of higher air temperatures in the lower troposphere is contributing to changes in the atmospheric circulation in the subarctic by reducing the potential impacts from the positive phase of the AO pattern, and perhaps contributing to the increased occurrence of the AW pattern.


1) Circulation

In 2008, the ocean surface circulation regime in the central Arctic was anticyclonic (clockwise) in winter and summer (Fig. 5.5). The intensity of motion was weaker than observed in 2007, consistent with changes in the observed sea level atmospheric pressure patterns (see section 5b). In winter the major flow stream removed sea ice from the Kara and Laptev Seas, while in the summer sea ice from the Canada Basin was transported toward the Fram Strait. Data from satellites and drifting buoys (Proshutinsky et al. 2009) indicate that the entire period of 1997–2008 has been characterized by a relatively stable anticyclonic ocean surface circulation regime. This circulation pattern was the result of a higher sea level atmospheric pressure over the Arctic Ocean, relative to the 1948–2008 mean, and the prevalence of anticyclonic winds. These conditions have significantly influenced the sea ice cover, oceanic currents, and ocean freshwater and heat content.

2) Water temperature and salinity

Upper-ocean temperatures in summer 2008 were not quite as high as in the record-breaking summer of 2007. Although the position of the September ice edge did not change significantly in 2008 relative to 2007, the timing of ice retreat was different. Early ice retreat from the Beaufort

![Fig. 5.4. Vertical cross section from 60° to 90°N along 180° longitude averaged for Oct–Dec 2003 through 2008 (years for which summertime sea-ice extent fell to extremely low values) for (a) air temperature and (b) geopotential height. Data are from the NCEP–NCAR reanalysis available online at www.cdc.noaa.gov.]

![Winter (DJFM) 2008](image1)

![Summer (JJAS) 2008](image2)

![Fig. 5.5. Simulated circulation patterns of the upper-ocean wind-driven circulation in (left) winter and (right) summer in 2008. Both patterns are identified as anticyclonic (clockwise). The intensity of anticyclonic circulation in summer 2008 has reduced relative to 2007 (see Proshutinsky and Johnson 1997 for details).]
Sea in 2008 led to anomalously high sea surface temperatures that exceeded even those in 2007 in this region (Fig. 5.6). However, ice retreat in the Chukchi and east Siberian Seas occurred relatively late in the summer, leading to near-normal or only slightly above-normal ocean warming (Fig. 5.6). This difference illustrates that the warming of the upper ocean is dependent not only on the position of the September ice edge but also on the time history of the ice cover over the summer. More specifically, ocean surface warming depends on the time history of atmospheric heat input to the sea surface, which depends both on atmospheric conditions (winds, clouds) and on the presence of the ice cover that acts to block this heat input (Steele et al. 2009, manuscript submitted to J. Geophys. Res.).

Changes in the AWCT varied regionally in 2008, reflecting temporal pulses in the Atlantic water flow volume, temperature, and salinity in the Fram Strait. The Atlantic water propagates cyclonically (counter-clockwise) along the Arctic Ocean continental slope, entering the Arctic Ocean via the Fram Strait west of Spitsbergen and leaving the Arctic via the Fram Strait east of Greenland. Observations at a NABOS (http://nabos.iarc.uaf.edu/) mooring in the vicinity of Spitsbergen (Fig. 5.7) along the entry point of the AWCT showed that the monthly mean AWCT at 260 m reached a maximum of ~3.8°C in November–December 2006. Subsequently, the temperature at this location has declined or cooled, reaching ~2.8°C in 2008. Observations at sections crossing the continental slope in the vicinity of Severnaya Zemlya also revealed cooling of AWCT by approximately 0.5°C (Fig. 5.7). This cooling signal has not reached central parts of the Arctic Ocean and the Beaufort Gyre of the Canada Basin (Proshutinsky et al. 2009). In the Beaufort Gyre region, the AWCT in 2008 was 0.80°–0.90°C, which is 0.10°C above AWCT observed in 2007 and 0.50°C above AWCT from pre-1990s climatology. In spring of 2008, data collected at the NPEO (http://psc.apl.washington.edu/northpole/index.html) indicate that the AWCT increased to nearly 1.4°C, which is about 0.1°C higher than observed in a 2007 survey and about 0.7°C higher than pre-1990s climatology.

![Fig. 5.6. Satellite-derived summer (JAS) SST anomalies (Reynolds et al. 2002) in (left) 2007 and (right) 2008, relative to the summer mean over 1982–2006. Also shown is the Sep mean ice edge (thick blue line).](image)

![Fig. 5.7. Temporal (°C) and spatial variability of the AWCT. Locations of sections are depicted by yellow thick lines. Mooring location north of Spitsbergen is shown by a red star. There is a decline of Atlantic water temperature at 260 m at mooring locations with a rate of 0.5°C per year starting at the end of 2006. Some cooling in 2008 is also observed at the sections crossing the continental slope in the vicinity of Severnaya Zemlya and in the east Siberian Sea (Polyakov et al. 2009, manuscript submitted to Geophys. Res. Lett.).](image)
Summer 2008 ship-based hydrographic surveys (Ashik, Sokolov, Frolov, and Polyakov 2008, personal communications) in different regions of the Arctic Ocean showed a continued freshening of the upper 20-m ocean layer, similar to 2007. In the 25–75-m layer, some salinification was observed in the central regions of Amundsen and Makarov Basins, while along the continental slope the water salinity remained unchanged relative to salinities observed in 2007. There was also some freshening of the deeper water layers in the Beaufort Gyre in 2008, as the surface freshening in this region was accompanied by Ekman pumping (Proshutinsky et al. 2009).

Data collected as part of the BGOS (www.whoi.edu/beaufortgyre/index.html) show that in 2000–08 the total freshwater summer content in the Beaufort Gyre has significantly increased relative to climatology of the 1970s (Arctic Climatology Project 1997, 1998; Fig. 5.8). In 2008, the center of the freshwater maximum remained shifted toward Canada as in 2007 but significantly intensified relative to 2007 (Fig. 5.8). As a result, the northwest part of the region is much saltier and the southeast region of the Beaufort Gyre is much fresher than in 2006–07 and, also, compared to 30 years ago. At some stations in the southeast of the Canada Basin the FWC reached the maximum observed value, increasing by as much as 11 m, which is 60% above climatology values. The freshening extends northward through the Canada and Makarov Basins to the Lomonosov Ridge (not shown). On the Eurasian side of the Lomonosov Ridge, the FWC anomaly is negative (water salinity was increased relative to climatology) with minimum FWC values of about −4 m (McPhee et al. 2009). The Beaufort Gyre heat content is significantly elevated relative to 1970s climatology (Arctic Climatology Project 1997, 1998; Fig. 5.8), but no significant changes relative to 2007 heat content were registered by the BGOS in 2008.

The Bering Strait is an important gateway to the Arctic Ocean. Preliminary observations from a mooring site, established and maintained since 1990 (Woodgate et al. 2006), suggest the 2007 annual mean transport through the Bering Strait is around 1 Sv (1 Sv = 10⁶ m³ s⁻¹), greater than 2006 but comparable with previous high years, such as 2004. The same is true of the freshwater flux through the strait. The heat flux, being largely determined by the total volume flux, is also high, but in this case it appears to be somewhat higher than the 2004 values.

3) Sea Level

Figure 5.9 shows SL time series from nine coastal stations in the Siberian Seas, having representative records for the period of 1954–2008 (Arctic and Antarctic Research Institute data archives). For the nine stations, the rate for 1954–89, after the GIA, was 1.94 ± 0.47 mm yr⁻¹. This compares to an estimated rate of 1.85 ± 0.43 mm yr⁻¹ along the Arctic coastlines over the same period, based on 40 arctic coastal stations (Proshutinsky et al. 2004). Addition of 1990–2008 data increases the estimated rate of SL rise for the
nine stations in the Siberian seas, beginning in 1954, to 2.68 ± 0.45 mm yr$^{-1}$ (after correction for GIA).

Until 1996, SL correlates relatively well with the times series of the AO Index and sea level atmospheric pressure at the North Pole (Fig. 5.9). In contrast, from 1997 to 2008 the SL has generally increased, despite the more or less stable behavior of AO and SLP. Possible reasons for the rapidly rising sea level are ocean expansion, due to heating and freshening of the Arctic Ocean, and increased rates of the Greenland ice sheet melt (see section 5f).

2) Sea-ice age and thickness

The age of the ice is another key descriptor of the state of the sea-ice cover, since older ice tends to be

![Fig. 5.9. The 5-yr running mean time series: annual mean sea level at nine tide gauge stations located along the Kara, Laptev, east Siberian, and Chukchi Seas' coastlines (black line). The red line is the anomalies of the annual mean AO Index multiplied by 3. The dark blue line is the sea surface atmospheric pressure at the North Pole (from NCAR–NCEP reanalysis data) multiplied by −1. Light blue line depicts annual sea level variability.](image)

at the end of winter when the ice is at its maximum extent, and September, when it reaches its annual minimum. Maps of ice coverage in March 2008 and September 2008 are presented in Fig. 5.10. The magenta line in the maps denotes the median ice extent for the period 1979–2000. The total area coverage in March was 15.2 million km$^2$, only 4% less that the 1979–2000 average of 15.8 million km$^2$. The area of reduced winter ice extent was located largely in the Barents Sea and the Sea of Okhotsk. The 2008 September summer minimum ice extent was 4.5 million km$^2$ and was not a record minimum. However, it was the second-lowest ice extent on record, only 0.3 million km$^2$ greater than 2007 and 36% below the 1979–2000 average. The largest retreats in September 2008 were found in the Beaufort and east Siberian Seas.

The time series of the anomalies in sea-ice extent in March and September for the period 1979–2008, computed with respect to the average from 1979 to 2000, are plotted in Fig. 5.11. The large interannual variability in September ice extent is evident. Both winter and summer ice extent exhibit a negative (decreasing) trend, with values of −2.8% per decade for March and −11.1% per decade for September.

![Fig. 5.10. Sea-ice extent in (left) Mar 2008 and (right) Sep 2008, illustrating the respective winter maximum and summer minimum extents. The magenta line indicates the median maximum and minimum extent of the ice cover, for the period 1979–2000. A—east Siberian Sea, B—Sea of Okhotsk, C—Bering Sea, D—Beaufort Sea, and E—Barent’s Sea. (Figures from the NSIDC Index: nsidc.org/data/seaice_index.)](image)